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Article

Sustainable alternatives to cement in structural engineering

Guosong Yang

School of Civil Engineering, Nanjing University of Technology, Nanjing 211800, China; yanggs2019@163.com

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Abstract: The environmental impact of ordinary Portland cement (OPC) production, particularly its high carbon emissions and energy consumption, has prompted the structural engineering community to seek more sustainable alternatives. This review examines a range of materials that can partially or fully replace OPC, including industrial by-products (e.g., fly ash, ground granulated blast furnace slag), geopolymers, natural pozzolans, and recycled construction waste. The article evaluates these alternatives in terms of their mechanical performance, durability, workability, and suitability for structural applications. Environmental and economic assessments, including life cycle analysis and cost considerations, are also discussed to provide a holistic view of sustainability. While many alternatives show promising performance and environmental benefits, wider adoption depends on overcoming technical challenges, regulatory gaps, and market inertia. This review highlights the need for integrated efforts in research, policy, and practice to transition toward more sustainable materials in structural engineering.

Keywords: sustainable construction, cement alternatives, fly ash, geopolymers, structural concrete

1. Introduction

Cement is the cornerstone of modern construction, forming the binding agent in concrete, the most widely used man-made material in the world [1]. The fact that it is found in all aspects of infrastructure, including buildings and bridges, dams, and highways, has made it (no pun intended) an inseparable part of the structural engineer. Nevertheless, notwithstanding its positive attributes in terms of performance and availability, the ordinary Portland cement (OPC) poses a serious issue of concern since it is not sustainable. Production of cement is, on the one hand, energy-intensive as it uses more than 30% the energy used in other industries; on the other hand, cement contributes a substantial amount of carbon emissions in the world, which is estimated to be up to 7–8 percent of the total amount of carbon emissions in the world. Such an environmental burden, along with the rising interest in depletion of resources and climate change, has fuelled the worldwide hunt for more sustainable alternatives [2,3].

The environmental impact of cement arises primarily from two sources: the calcination of limestone (which releases CO_2) and the high-temperature processing required to form clinker. Each ton of cement produced results in nearly 1 t of CO_2 emissions. With growing construction demands, especially in rapidly urbanizing regions, these figures are projected to rise unless decisive changes are made in material sourcing and construction practices. It has therefore become paramount to not only shift towards environmental sustainability but also attain long-term economic and resource-efficient construction through the independence of utilization of traditional cement [4].

The construction materials that cause less environmental degradation, but with adequate mechanical properties relevant to building structures and durability of materials, are referred to as sustainable construction materials. During the last few decades, various alternatives to OPC have been discussed by researchers, practitioners, and available alternatives to build many alternatives to OPC have been built in three major groups: industrial by-products, natural materials, and innovative binders, including the geopolymers. These options have the potential of having reduced carbon footprints, waste reduction with recycling, and even enhanced halo improvement characteristics of certain applications. Nevertheless, their adoption in building structural engineering practice is still sparse because of technical, regulatory, and economic constraints [5].

Some of the most thoroughly examined replacements are industrial by-products such as fly ash, ground granulated blast-furnace slag (GGBS), and silica fume. These can be commonly found in energy production and metallurgy, and can make an equal or partial cement replacement in concrete, helping prolong its strength and durability. Simultaneously, geopolymer technology, also known as aluminosilicate technology or aluminosilicate fuels or aluminosilicate charcoal or aluminosilicate fuel, has also shown potential of being a leading direction to zero-cement construction. Such binders not only exclude the calibration of limestone, but they also use the industrial wastes in a multi-timely manner. Also, older materials such as lime, natural pozzolans (volcanic ash, etc.), and bio-based ashes (rice husk ash, etc.) have re-emerged as possibilities in certain structural and local situations [6].

The integration of the materials, however, comes with problems. There have been questions on their performance in the long run under different environmental conditions, compatibility with the current construction standards, and their behaviour in load-bearing constructions and those with seismic activity. Furthermore, the problematic areas of material consistency, availability, cost efficiency, and regulatory endorsement remain problematic areas to make it popular. The quality control and standardization are a challenge in most situations due to the variability of alternative binders, particularly the industrial wastes. Moreover, adoption can be hindered by a lack of familiarity among many structural engineers and contractors, even where there has been proven technical feasibility [7].

Economically and policy-wise, integration of green cement alternatives should likewise consider life cycle assessments (LCA), energy payback periods, and possible incentives based on green building certifications or governmental incentives. Climate targets are becoming more ambitious, especially within international systems and treaties, like the Paris Agreement, which means that standards are changing with regard to construction. This trend has opened a strategic plan to place sustainable practices in the mainstream of structural engineering [8].

This review article aims to synthesize current knowledge and developments in sustainable alternatives to cement for structural applications. It will explore the types of alternatives available, assess their mechanical and environmental performance, and evaluate the barriers and opportunities associated with their use. By presenting both the technical and socio-economic dimensions of cement replacement, this article seeks to contribute to a growing body of literature that supports the shift toward greener and more resilient infrastructure [9].

In summary, while traditional cement has long underpinned the strength and durability of our built environment, its continued dominance comes at an unsustainable environmental cost. The search for and adoption of viable cement alternatives in structural engineering is not only a scientific and technical imperative—it is an environmental necessity. Through innovation, interdisciplinary collaboration, and supportive policy frameworks, the next generation of construction materials may well succeed in reducing emissions without compromising the integrity of our structures. This article explores how close we are to achieving that goal—and what steps remain ahead.

2. Types of sustainable cement alternatives

The search for sustainable alternatives to Portland cement has led to the identification and development of various materials that either partially replace or fully substitute cement in structural applications. These alternatives not only help reduce CO_2 emissions and energy use but also enhance the performance of concrete in some cases. They generally fall into four categories: industrial by-products, geopolymer binders, natural pozzolanic materials, and recycled materials. This section examines each category in detail.

2.1. Industrial by-products

The most implemented and studied substitutes of cement, though, are industrial by-products. Such materials are generally pozzolanic, i.e., siliceous or aluminous components, which, in reaction with water and calcium hydroxide, produce compounds with cementitious properties. The by-products are mainly fly ash, Ground Granulated Blast Furnace Slag (GGBS), and silica fume.

Fly Ash is a coal combustion by-product that occurs as fine powder. It is divided into Class F (low calcium) and Class C (high calcium). Workability is enhanced, the heat of hydration is lowered, and the long-term strength and durability of the concrete are enhanced by using fly ash. It has been largely utilized in blended cement and concrete.

GGBS is a by-product of iron production in blast furnaces. GGBS is highly cementitious and is often used in conjunction with OPC. It enhances sulfate resistance and reduces permeability, making it suitable for marine and underground structures. Silica Fume is a fine powder generated during silicon and ferrosilicon alloy production. Its high pozzolanic activity makes it effective in producing high-strength, low-permeability concrete. Due to its small particle size, it also improves the bond between cement paste and aggregates.

These by-products not only offer technical advantages but also divert significant industrial waste from landfills, contributing to circular economy goals. However, their availability is dependent on regional industrial activity and may be limited in areas without relevant power or metallurgical plants [10–13].

2.2. Geopolymers and alkali-activated materials

Geopolymers constitute an emerging class of synthetic aluminosilicate binders produced through the chemical reaction between aluminosilicate-rich precursor materials and alkaline activating solutions. Common precursors include industrial by-products and natural materials such as fly ash, metakaolin, ground granulated blast furnace slag (GGBS), and certain clays, while the activation is typically achieved using solutions of sodium hydroxide, sodium silicate, or their combinations. This process, referred to as alkali activation, fundamentally differs from conventional cement manufacturing in that it eliminates the need for high-temperature clinker formation, thereby significantly reducing energy consumption. From a performance perspective, geopolymer concretes are known to develop high compressive strength, often at early ages, and exhibit excellent resistance to fire, chemical attack, and sulfate-rich or acidic environments. Additionally, their dense microstructure contributes to relatively low shrinkage and enhanced long-term durability compared with ordinary Portland cement (OPC)–based systems. Environmentally, geopolymer binders offer substantial sustainability advantages, with life-cycle assessments indicating potential reductions in carbon emissions of up to 80% relative to OPC, depending on the choice of precursor materials and the production pathways of alkaline activators. Despite their promise, challenges remain in terms of standardization, curing conditions (some require elevated temperatures), and the handling of chemical activators, which may pose health and safety concerns [14].

2.3. Natural pozzolanic materials

These are naturally occurring materials that exhibit pozzolanic behaviours, often after thermal or mechanical treatment. They have been used in construction for centuries (e.g., Roman concrete). Examples of such materials include volcanic ash, calcined clay, metakaolin, and Rice Husk Ash (RHA). Volcanic ash is rich in amorphous silica and alumina; it reacts with calcium hydroxide to form cementitious compounds. Calcined clay and metakaolin are produced by heating kaolinite-rich clays. Metakaolin enhances early strength and improves resistance to chloride penetration. RHA is a by-product of rice milling and combustion, and it is high in amorphous silica and can be an effective cement replacement. Natural pozzolans are renewable and often locally available, making them suitable for use in rural or developing regions. However, their properties can vary significantly depending on the source, which complicates their standardization [15].

2.4. Recycled materials and construction waste

In recent years, the principles of the circular economy and zero-waste construction have driven increasing interest in the utilization of recycled construction and demolition waste as alternative cementitious materials. Rather than being disposed of in landfills, these wastes can be processed and valorized as supplementary or partial replacements for conventional cement binders, thereby reducing both environmental burdens and raw material consumption.

Among these materials, recycled concrete fines (RCF) obtained by finely grinding demolished concrete have demonstrated latent binding potential, particularly when chemically activated using alkaline solutions. When properly processed, RCF can contribute to strength development and microstructural densification in blended or alkali-activated systems. Waste glass powder, produced by milling discarded glass to a fine particle size, exhibits notable pozzolanic reactivity due to its high amorphous silica content. When incorporated into cementitious systems, it can participate in secondary hydration reactions, improving durability while simultaneously diverting glass waste from landfills.

Similarly, brick dust, derived from crushed fired clay bricks, can act as a supplementary cementitious material when finely ground. Its aluminosilicate composition enables pozzolanic reactions with calcium hydroxide, enhancing long-term strength and contributing to sustainable resource utilization in concrete production. These materials promote resource efficiency and reduce landfill use. However, issues of contamination, variable quality, and inconsistent reactivity require careful processing and quality assurance [16].

2.5. Comparison of alternatives

The variety of sustainable alternatives to cement offers a rich palette of materials that can be tailored for different structural and environmental requirements. While some—like fly ash and GGBS are already widely used in commercial concrete, others, like geopolymers and agricultural ash-based materials, are still emerging. The next section will explore how these materials perform in structural applications, including mechanical properties, durability, and practical challenges in construction contexts [17]. A detailed comparison is given in **Table 1**.

Table 1. A comparison of cement alternatives.

Alternative material	Key benefits	Limitations
Fly Ash	Reduces heat, improves durability	Availability depends on coal usage
GGBS	Improves strength and sulfate resistance	Requires grinding and a consistent supply
Geopolymers	Very low CO_2 emissions, high performance	Requires alkaline activators, less standardized
Natural Pozzolans	Abundant, often renewable	Varying quality, lower early strength
Recycled Materials	Reduces waste, promotes circular economy	Processing and quality control challenges

3. Performance characteristics and structural suitability

The successful use of sustainable cement alternatives in structural engineering depends not only on environmental advantages but also on their technical performance. Structural materials must meet rigorous standards for strength, durability, workability, and long-term behaviour under various loading and environmental conditions. This section evaluates the mechanical properties, fresh-state behaviour, durability, and application feasibility of alternative binders, along with the practical challenges and limitations involved in using them.

3.1. Mechanical properties

The fundamental requirement of any material used in structural engineering is its capacity to safely resist both compressive and tensile stresses under service and ultimate loading conditions. In this context, the mechanical performance of sustainable cement alternatives exhibits considerable variability, largely influenced by the type of binder employed, mix design parameters, curing regimes, and the use of chemical or mineral additives.

In terms of compressive strength, alternative cementitious systems display diverse strength development characteristics. Fly ash–based concretes typically exhibit slower early-age strength gain compared to ordinary Portland cement (OPC) concrete; however, their long-term strength often equals or surpasses that of OPC at later ages, such as 28 or 56 days, due to sustained pozzolanic reactions. Concretes incorporating ground granulated blast furnace slag (GGBS) frequently demonstrate enhanced compressive strength alongside a reduced heat of hydration, making them particularly suitable for mass concrete applications where thermal cracking is a concern. Geopolymer concretes have shown the ability to attain high compressive strengths commonly in the range of 60–80 MPa—even at early curing stages, especially when subjected to elevated-temperature curing. Natural pozzolanic materials, such as metakaolin, are known to improve both early-age and long-term strength, whereas others, including rice husk ash, often require carefully optimized mix designs to achieve comparable mechanical performance.

With respect to tensile and flexural behavior, many cement alternatives tend to exhibit slightly lower strength than conventional OPC-based concrete. This limitation can be effectively addressed through the incorporation of fibers or suitable admixtures, which enhance crack resistance and post-cracking behavior. Geopolymer concretes, in particular, may demonstrate improved tensile and flexural performance due to their dense and refined microstructure; however, they can also exhibit brittle failure characteristics in the absence of adequate reinforcement.

The modulus of elasticity of blended and geopolymer concretes is generally lower than that of OPC concrete, reflecting differences in microstructure and binder composition. This reduced stiffness may influence deflection behavior and serviceability performance in structural elements, necessitating careful consideration during structural design. Overall, while sustainable cement alternatives can meet structural performance requirements, their mechanical characteristics must be thoroughly evaluated and appropriately accounted for in engineering applications [18].

3.2. Workability and setting time

The fresh-state properties of concrete, including workability, consistency, and setting time, play a crucial role in determining the ease of mixing, placing, compaction, and finishing during construction. These properties are particularly important when alternative cementitious materials are used, as their physical and chemical characteristics can significantly alter the behavior of concrete in its plastic state.

Workability is strongly influenced by the nature of the binder. Fly ash is well known for improving workability due to the spherical shape of its particles, which act as microscopic ball bearings and enhance flowability. In contrast, highly reactive and finely divided materials such as silica fume and metakaolin tend to reduce workability by increasing water demand and surface area, often necessitating the use of superplasticizers to achieve acceptable consistency. Geopolymer mixtures can exhibit a sticky or stiff consistency depending on the precursor materials, activator composition, and mix proportions, and therefore require careful handling and practical experience to ensure proper placement and compaction.

Setting time is another critical fresh-state parameter affected by the use of cement alternatives. The incorporation of fly ash and ground granulated blast furnace slag (GGBS) commonly leads to delayed setting, which can be advantageous in mass concrete applications by reducing thermal stresses but may pose challenges in cold-weather construction or projects requiring rapid strength gain. Geopolymer binders exhibit highly variable setting behavior, ranging from rapid to significantly delayed setting, depending on factors such as activator concentration, curing temperature, and mix chemistry, making precise control essential. Natural pozzolans and recycled materials often display inconsistent setting characteristics, and trial mixes are typically required to establish workable and reliable setting times for practical applications.

3.3. Durability and long-term performance

Durability is a critical consideration in structural engineering, particularly for structures exposed to aggressive environments such as marine conditions, industrial atmospheres, or repeated freeze–thaw cycles. Sustainable cement alternatives can significantly influence the long-term performance of concrete through their effects on microstructure, permeability, and chemical stability.

In terms of resistance to chloride and sulfate attack, materials such as GGBS and fly ash enhance durability by refining the pore structure and reducing permeability, thereby limiting the ingress of aggressive ions. Geopolymer concretes generally exhibit excellent chemical resistance, especially against acidic and sulfate-rich environments, largely due to the absence of calcium hydroxide and the formation of a stable aluminosilicate matrix. Similarly, supplementary materials such as rice husk ash and metakaolin have been shown to reduce chloride penetration and mitigate the risk of alkali–silica reaction (ASR), contributing to improved durability.

Carbonation behavior represents an important design consideration for blended and geopolymer concretes. Owing to their lower calcium content and distinct pore chemistry, these materials may be more susceptible to carbonation compared to conventional OPC concrete, which can influence reinforcement corrosion risk if not properly accounted for in design and cover specifications.

Freeze–thaw resistance in alternative binder systems has shown mixed performance, depending on the type of binder, air-entrainment practices, and overall mix design. In some cases, the use of fly ash without adequate air-void control may reduce freeze–thaw durability, highlighting the need for appropriate mix adjustments. Shrinkage and creep behavior also vary among cement alternatives. While materials such as silica fume may increase drying shrinkage due to their fine particle size, fly ash and GGBS can reduce shrinkage over time by promoting gradual hydration. Geopolymer concretes typically exhibit low creep; however, they may be prone to higher drying shrinkage unless suitable additives or curing strategies are employed [19]. Mechanical and durability performance of different cement alternatives is summarized in **Table 2**.

Table 2. Mechanical and durability performance of cement alternatives.

Alternative material	Compressive strength development	Durability performance	Key structural implications
Fly ash concrete	Slow early, high long-term strength	Improved chloride & sulfate resistance	Mass concrete, pavements
GGBS concrete	Moderate early, high long-term strength	Excellent sulfate & marine resistance	Marine & underground structures
Silica fume concrete	High early and ultimate strength	Very low permeability	High-strength elements
Geopolymer concrete	High early strength (60–80 MPa)	Excellent acid & fire resistance	Precast, aggressive environments
Metakaolin concrete	Enhanced early and later strength	Reduced ASR and chloride ingress	Structural repairs
Rice husk ash concrete	Moderate strength (mix dependent)	Improved impermeability	Low-cost structures

3.4. Challenges and limitations

Despite their advantages, cement alternatives face several technical and practical barriers. Waste-based materials like fly ash or RHA can vary significantly depending on the source, leading to unpredictable performance. Many standards (e.g., ASTM, EN, and IS codes) have limited coverage of alternative binders, making approval for structural use more difficult. Construction crews may lack experience with handling and curing non-OPC mixes, affecting quality control. Some materials (e.g., geopolymers) may need special curing conditions such as elevated temperatures, which complicates field implementation.

In terms of structural performance, many sustainable alternatives to cement offer comparable—or in some cases superior- mechanical and durability properties. However, their success in structural applications depends on mix design optimization, standardization, and construction adaptability. While materials like fly ash and GGBS have already found a place in practice, more advanced alternatives such as geopolymers and bio-based ashes require further research, testing, and field validation. The next section will focus on environmental and economic assessments to evaluate the overall sustainability of these materials [20].

4. Environmental and economic assessment

While technical performance is crucial, the environmental and economic viability of sustainable cement alternatives ultimately determines their large-scale adoption in structural engineering. This section discusses the performance of these materials in life cycle assessments (LCA), cost-benefit analysis, and within the regulations and policies. It highlights the need to consider an alternative to cement based on the tri-pronged approach of sustainability and not merely on its strength or durability proxies.

4.1. Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is a generalized technique to assess the total environmental impact of a given material or system during the time ascribed to its entire life cycle- namely, extraction of raw materials and end-of-life disposal. For cement alternatives, LCA reveals significant sustainability benefits. When applied to cementitious materials, LCA provides critical insights into the environmental advantages of sustainable cement alternatives over conventional ordinary Portland cement (OPC). Numerous LCA studies have demonstrated that alternative binders can substantially reduce greenhouse gas emissions, energy demand, and resource depletion while supporting more circular material flows.

One of the most significant benefits revealed by LCA is the reduction in carbon dioxide emissions. The production of OPC is highly carbon-intensive, with approximately 0.9–1.0 t of CO_2 emitted per ton of cement, largely due to limestone calcination and high-temperature kiln operation. In contrast, industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and rice husk ash (RHA) are typically considered waste materials from existing industrial or agricultural processes. As a result, their use as cement replacements introduces minimal additional processing emissions, leading to carbon footprint reductions of up to 70–90% compared to OPC. Geopolymer binders also exhibit substantial emission reductions, generally in the range of 40–80%, although their environmental performance depends on the type and dosage of alkaline activators and the energy sources used in their production.

Energy consumption is another critical parameter evaluated through LCA. OPC manufacturing requires extremely high energy input due to kiln firing temperatures of approximately 1450 °C. Conversely, materials such as fly ash and GGBS are generated as by-products of already energy-intensive processes, and their utilization as binders avoids the need for additional high-temperature processing. Calcined clays and metakaolin require thermal activation at temperatures typically between 600 and 800 °C, which still represents a substantially lower energy demand than OPC production. Consequently, alternative binders offer notable energy savings at the material production stage.

From a resource conservation perspective, sustainable cement alternatives play an important role in reducing the depletion of non-renewable raw materials, particularly limestone. By partially or fully replacing OPC, these materials help preserve natural mineral reserves and decrease the volume of waste sent to landfills. The incorporation of construction and demolition waste further strengthens circular economy principles by reintegrating end-of-life materials back into the construction value chain.

Water usage and pollution potential are also favorably influenced by the adoption of cement alternatives. Many alternative binders require less water during mixing or curing, and the avoidance of kiln-based production significantly reduces air pollutants such as particulate matter, nitrogen oxides (NOx), and sulfur oxides (SOx) associated with fossil fuel combustion. Collectively, LCA results highlight the substantial environmental benefits of replacing OPC with more sustainable cementitious materials [21–23].

4.2. Cost analysis

A common perception is that sustainable alternatives are more expensive or less economically viable than OPC. However, this depends on local availability, processing requirements, transportation costs, and scale of application. In terms of material costs, fly ash and GGBS are frequently less expensive than OPC and, in some regions, may be obtained at minimal or no cost directly from industrial producers. Geopolymer systems, on the other hand, can incur higher initial costs due to the price of alkaline activators such as sodium hydroxide and sodium silicate. The cost of natural pozzolans varies widely depending on regional geology, extraction methods, and processing requirements, making them more economically viable in areas with local deposits.

Processing and handling costs also influence overall economic performance. Certain materials, including rice husk ash and silica fume, require controlled combustion, fine grinding, or special handling procedures, which can increase processing expenses. However, the reduced demand for OPC often results in lower energy consumption and transportation costs, partially offsetting these additional expenditures.

At the construction stage, alternative binders can offer indirect economic benefits. Improved workability associated with fly ash and slag blends can reduce labor demands and equipment wear, while lower heat of hydration can minimize cracking and associated repair costs. More importantly, the enhanced durability of concrete incorporating GGBS, geopolymers, or high-quality pozzolans can significantly reduce long-term maintenance and rehabilitation costs, particularly in aggressive environments such as marine or sulfate-rich conditions.

From a lifecycle perspective, these durability benefits translate into substantial cost savings over the service life of a structure. Additionally, government incentives, tax benefits, and green building subsidies can further improve the economic viability of sustainable cement alternatives by offsetting higher initial material costs [24].

4.3. Policy and regulatory support

The widespread adoption of sustainable cement alternatives is strongly influenced by the regulatory environment, standards development, and policy incentives. In recent years, several countries and international organizations have taken steps to encourage the use of low-carbon and resource-efficient construction materials.

Green building certification systems such as LEED in the United States, BREEAM in the United Kingdom, and the Indian Green Building Council (IGBC) rating system provide credits for the use of supplementary cementitious materials and recycled content. These certifications enhance the market value of construction projects and attract environmentally conscious investors and stakeholders.

At the standards level, codes such as ASTM C618 for fly ash, EN 197-1 for blended cements, and various Indian Standards permit the partial replacement of OPC in structural concrete. However, newer binder systems, particularly geopolymers, often fall outside conventional prescriptive standards. Their approval typically relies on performance-based criteria, pilot projects, or project-specific testing protocols.

Government policies also play a critical role through mechanisms such as tax incentives, carbon pricing schemes, and material subsidies aimed at reducing emissions from the construction sector. Public infrastructure projects increasingly incorporate sustainability requirements into procurement specifications, thereby creating market demand for low-carbon binders. Nevertheless, regulatory conservatism and the slow pace of code development remain significant barriers, and standardized testing procedures for non-OPC concretes have yet to be globally harmonized [25–28].

4.4. Regional considerations and supply chains

The environmental and economic performance of sustainable cement alternatives is highly dependent on regional conditions, including material availability, transportation infrastructure, and industrial capacity. In developed economies, industrial by-products such as fly ash and GGBS are well integrated into existing supply chains, supported by established standards and strong institutional backing for green construction practices. In contrast, developing regions may benefit more from locally available natural pozzolans and agricultural residues such as rice husk ash or calcined clays, which can offer cost-effective and environmentally appropriate solutions. Localizing material supply chains reduces transportation-related emissions and enhances economic efficiency, particularly for large-scale infrastructure projects. Tailoring binder selection to regional resource availability is, therefore, essential for maximizing sustainability benefits.

Overall, environmental and economic assessments consistently demonstrate that sustainable cement alternatives—particularly fly ash, GGBS, and geopolymers- can deliver substantial reductions in carbon emissions and energy consumption while offering competitive or lower lifecycle costs. When supported by appropriate policies, updated standards, and regionally optimized supply chains, these materials represent a viable pathway toward more sustainable structural engineering practices. However, project-specific LCA and cost analyses remain essential to ensure optimal material selection and implementation [29,30]. **Table 3** provides a summary of the arguments for LCA, cost, and policy relevance.

Table 3. Environmental and economic comparison of OPC and alternatives.

Binder type	**CO_2 emissions reduction**	**Energy demand**	**Cost trend**	**Sustainability advantage**
Ordinary Portland Cement (OPC)	Baseline (high)	Very high	Moderate	Well-established but carbon-intensive
Fly ash / GGBS blends	50–90% lower	Low	Low	Strong circular economy benefits
Geopolymers	40–80% lower	Moderate	Moderate–high	Near-zero cement pathway
Natural pozzolans	40–70% lower	Low–moderate	Low	Regional sustainability
Recycled binders	30–60% lower	Low	Low	Waste reduction & landfill diversion

5. Conclusion

The urgent need to reduce the environmental impact of construction has brought the role of ordinary Portland cement (OPC) under critical scrutiny. As one of the most carbon-intensive materials used in infrastructure, cement contributes significantly to global greenhouse gas emissions and resource depletion. In this review, the variety of all the different sustainable options relating to structural engineering has been investigated, from the simple options of industrial waste like fly ash and GGBS, to more sophisticated binders like geopolymers, to all-natural and recycled materials like rice husk ash and construction waste.

These alternatives do provide a hopeful route of reducing the amount of a construction's carbon footprint without sacrificing, and instead increasing, mechanical performance and durability. Fly ash and slag are already in wide use when mixing with cement, and these geopolymers have proven to be outstanding in terms of chemical resistance and compressive strength. The natural pozzolans and recycled materials are further additions to the range of possibilities, particularly in the regions where the industrial infrastructure is poor.

Many of these options have been used to meet or surpass structural needs on a performance basis in a well-engineered fashion. Nevertheless, their implementation is usually impeded by the following types of factors: variability of raw materials quality, the absence of standardization, the lack of familiarity among practitioners, and inconsistent governmental assistance. The challenges outlined here suggest maintaining research, formulating newer codes and standards, and providing more education in the construction sector.

Environmental and economic reviews have shown that sustainable options are not merely more environmentally friendly with smaller CO_2 emissions and energy requirements, but can also lead to savings in the long term due to their better durability and the decrease in maintenance. In addition, the adoption of more stringent environmental standards by governments and institutions, as well as the encouragement of green construction activities, is making the transition to an alternative binder a regulatory and market necessity. Going forward, this ideal future in terms of sustainable structural engineering will demand a complex strategy: the need to promote innovation in material science, the need to revise the policy frameworks, the need to invest in the regional supply chain, and the need to raise awareness among stakeholders. It is by meeting these options that the construction sector can potentially limit its environmental demeanour and strive to establish safe, sound, and long-lasting structures.

To sum it up, although it is not unreasonable to expect that, at least in the short run, the traditional cement will continue to figure as a constituent of structural engineering, the term of sustainable alternatives is maturing rapidly, barring a monumental change towards the future of our constructions. With appropriate mixes of technology, policy, and practice, sustainable cement alternatives can not only be viable but also normal when it comes to building tomorrow's infrastructure.

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